XVII th World Congress of the International Commission of Agricultural and Biosystems Engineering (CIGR)

Hosted by the Canadian Society for Bioengineering (CSBE/SCGAB)
Québec City, Canada June 13-17, 2010

GRID BASED RAINFALL-RUNOFF GIS MODELLING TO STUDY THE ANTHROPOGENIC EFFECT ON THE HYDROLOGY OF A SMALL WATERSHED

M. GREPPI, G. SENES

[1] M. Greppi, Department of Agricultural Engineering, State University of Milan, via Celoria 2 20133 Milano, Italy, mauro.greppi@unimi.it
[2] G. Senes, giulio.senes@unimi.it

CSBE100546 – Presented at Section 1: Land and Water Engineering Conference

ABSTRACT - In the Po basin urban development, land use change and variations in rain intensity have influenced watershed runoff and increased floods. In order to better study the anthropogenic effect on the basin hydrology the Olona river watershed proved to be an interesting small catchment to test. It went through a rapid change from agricultural land to urbanized and partly forest areas over the period 1954 – 1994. The Olona River is known for frequent flooding along its course and in some districts of Milan city. Using SCS-CN methodology, a rainflow-runoff model was calibrated with the observed outflow data in the Ponte Gurone station in the upper Olona basin (≈110 km^2). The extreme rainfall data series of three meteorological stations near and inside the watershed are statistically elaborated to obtain the depth duration frequency curves, used as the model input data. Basin concentration time and SCS parameter I_a (Initial abstraction) values are chosen to fit the model results and the observed discharges in the two rainfall intensity classes tested. Within the upper Olona basin, waterproof surfaces increase, leading to less infiltration and a quicker runoff, and produce higher outflow peaks. Model results give an estimate of land use change effect on the basin rainfall-runoff process change.

Keywords: Rainfall, runoff, land cover change, GIS modelling

INTRODUCTION Watershed hydrology is determined partly by the land cover. Different degrees of soil covering as well as soil exploitation can cause different processes of precipitation division into the watershed area. Over the last few decades floods have been the most costly natural disaster in Europe, and over the last few years flood frequency has increased. They usually concern areas with high populations, intensive land uses and increasing economic activities, hence very vulnerable to flooding disasters. Opinions vary on the causes of this incremented frequency (Tu *et al.*, 2006). Nevertheless, the anthropogenic evolution due to the expansion of urban areas is having a significant impact on the hydrological responses within the catchment area.

Cropland and urban land yield more flood volumes, higher peak discharges and shorter flow travel times than grassland or woodland. Increased runoff from cropland is mainly due to the removal of native vegetation and soil compaction, which decrease soil infiltration capacity. Increased runoff from urban areas results from impervious surfaces that prevent infiltration of water into soils. Less runoff is produced from undisturbed grassland and woodland areas, due to a higher interception of precipitation by the vegetation canopy, the dense network of roots that increase infiltration capacity and soil porosity, as well as accumulated organic debris on the surface that increases depression storage capacity and overland flow retention time. Moreover, dense vegetation causes higher evapotranspiration and less runoff water (Liu *et al.,* 2006).

Abrupt changes in watershed response can occur as a result of land use change and can be particularly severe at small scales, but in some case there are instances of large scales influences (Bloschl *et al.,* 2007). Land cover change will not only directly impact on runoff through affecting runoff generation processes but also indirectly through feedbacks with local climate (Pielke, 2005). Stream degradation results from a collection of individual decisions and actions that lead to altered stream conditions. Hydrologic consequences of urban development have long been documented for individual storms (Leopold, 1968; Hollis, 1975), but such consequences over longer periods are scarcely explored. Most analysts describe the consequences of changing land cover for the hydrological processes such as timber harvest on the water yield (Stednick, 1996), forest harvest on peak stream flow (Storck et al., 1998), vegetation change on basin hydrology (Matheussen et al., 2000; VanShaar et al., 2002) and urbanization on storm runoff generation (Niehoff et al., 2002). These studies mainly concentrate on one specific land cover change. In this study it is attempted to evaluate different land cover developments and their combined impacts. Land Use Planning can be considered as an important tool in catchment hydrology and in water management decision-making processes. Remember that the consequences of any decisions taken now will have to be lived with for a long time into the future (Ashley, 2006).

DATA AND METHODS 1 Urbanization diminishes the capacity of soils to absorb precipitation, and as a consequence of that, unless proper “countermeasures are taken” throughout the catchment area, an increase in discharge volumes and a decrease in hydrological response time all over the area will ensue. Such a concurrence of events would lead to more frequent flood episodes for equal peak flows or, conversely, to higher flows and volumes for equal expected frequency. The absorption capacity of any particular soil depends on its structural characteristics, on the vegetation it may be covered by, and finally on the ways its surface layer is being more frequently used. The percentage amount of precipitation that contributes to flood discharges also depends on the specific nature of what covers the soil. Both the infiltrated amount and the amount lost in evapotranspiration will vary depending on whether there is vegetation covering the surface area or not. The permeability change of the soil surface due to urbanization has an important effect on the hydrological runoff. A contribution to better understand this process is coming from the historical runoff measurements in the Ponte Gurone station of the Po Basin Hydrometeorological Agency, located, South of Varese, on the Olona River. This river is known for the frequent flooding along its course in the plane before Milan and of some Milan city districts. The working period (1939 – 1986) coincides with Varese great urbanization development. This is a small pre Alpine watershed where happens a wide agricultural surface change with expansion of urban areas in a first period and, after the park constitution (1985), of woods (Figure 1).

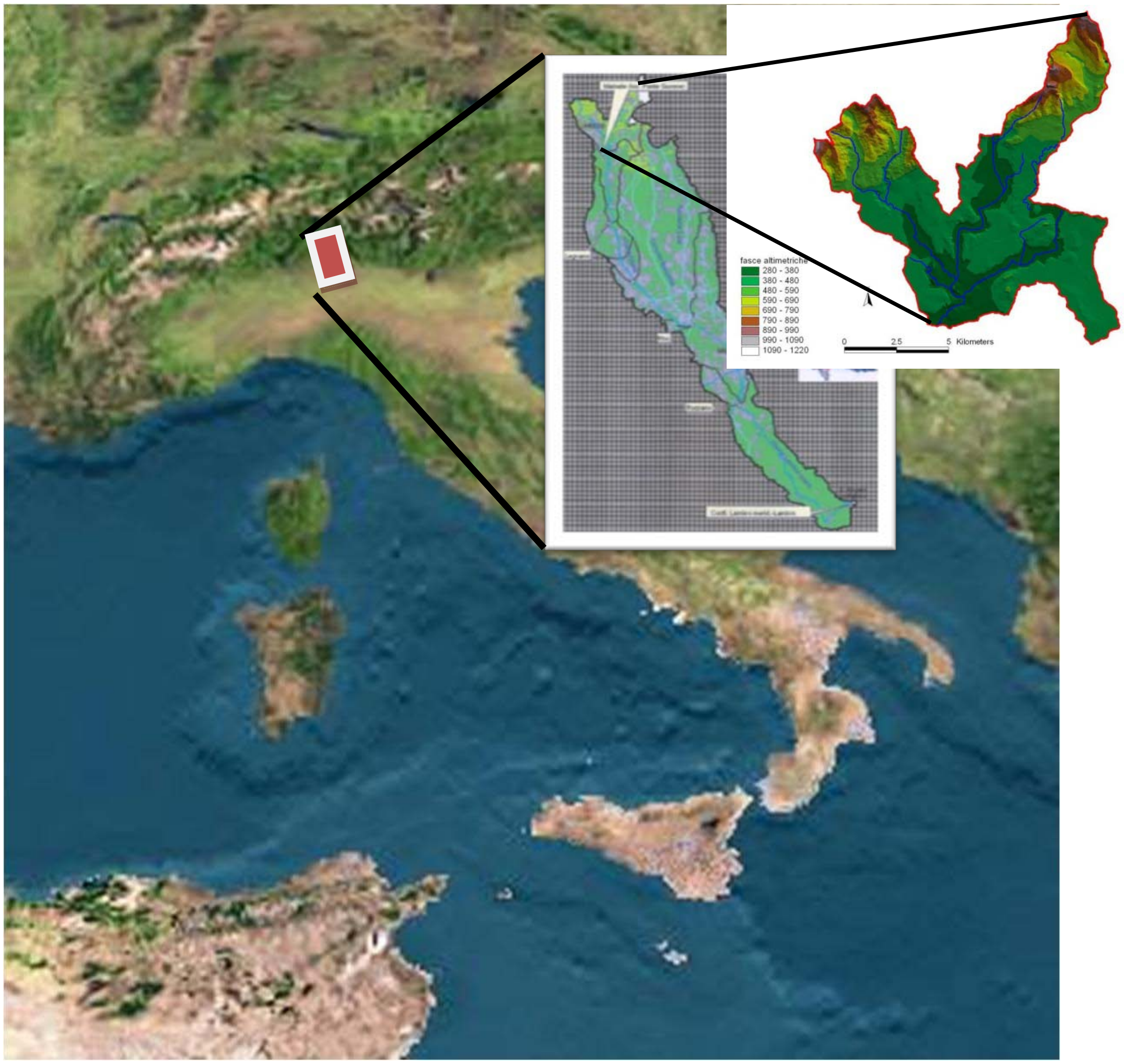

Figure 1. The Olona basin and the upper watershed closed at Ponte Gurone.

Methodology Giving the high number of hydrologic models, model selection is difficult. A good model has to be simple, accurate, realistic etc. The performance of a hydrologic model is highly dependent on the hypothesis of the model, the data for simulation input and the model structure. Underestimating or misunderstanding these factors and the relationship among them may tremendously mislead the interpretation of the results of the hydrologic models. There are several uncertainties such as on: model structure, model parameters, model validation and on parameters calibrations. Many methodologies have also been proposed to identify and analyse these uncertainties of hydrologic simulation (Chiang et al., 2007). Sensitivity studies give hydrologists the knowledge about the way in which uncertainty factors impact the hydrologic models through observing the way models respond to them.

In our study we assumed that the simple model used, with its uncertainties, works correctly in order to compare two changed scenarios of the selected small watershed. The Olona river watershed at Ponte Gurone proved to be an interesting small catchment as a study area. Its rapid change from agricultural land to urbanized areas demonstrated a clear change in basin runoff, during the years when river flow levels were measured. Our aim is to compare two changed scenarios due to the anthropogenic action and their effects on the hydrologic outflow, in the same meteorological conditions. The model is not accurate enough to describe in detail the runoff process, but it can be used to compare the watershed flows in two different land cover conditions.

The first phase of the study aims to calculate changes in time of the land area covered by vegetation, investigating the land use within the study area in different time thresholds. Given the purpose of the study and depending on availability of information, it was decided to choose as time thresholds 1954 and 1994. The land use map of 1954 was obtained from photo-interpretation of IGMI (Italian Geographical Military Institute) 1954 black & white aerial photos (average scale 1:33.000). A GIS (Geographical Information System) database (in ESRI shapefile format) was created through digitalization on IGMI topographic maps at scale 1:25,000. The land use classes identified, consistent with the purpose of the study, are "urbanized land", "woodland" and other "vegetated land" (Fig. 2). These classes are easily obtained with the photo-interpretation and sufficiently articulated for the successive Curve Number calculation. The land use map of 1994 was obtained by the reclassification of information contained in the vector GIS database "CT10" of Lombardy Region (acquisition scale of 1:10,000). The land use classes identified are the same of the 1954 (Fig. 3).

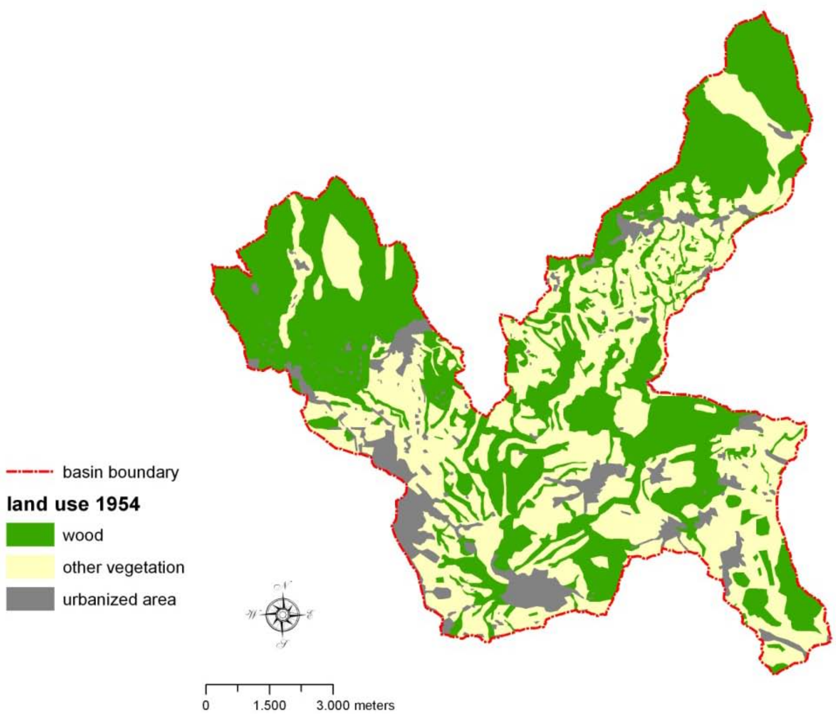

Figure 2. 1954 land use map.

Comparing the land use data, the study area shows for the period 1954-94:

- an increase (+20%) of the woodland class (+850 ha),
- a great decrease (-46%) of the Vegetated land class area (-1800 ha),
- a great increase (+111%) of the urbanized land class area (+950 ha).

This total variation shows a variability depending on the average elevation.

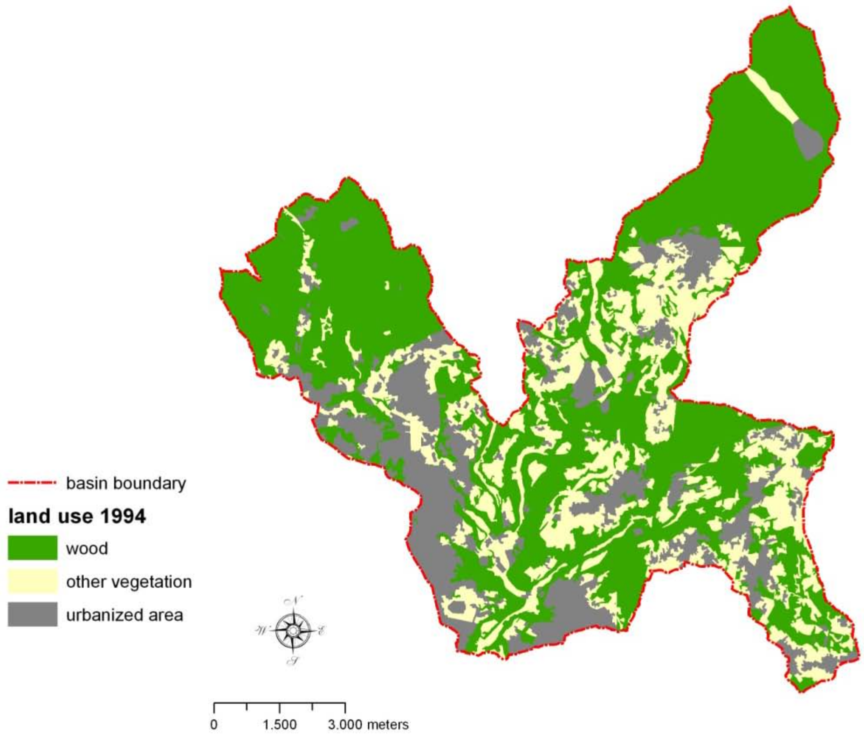

Figure 3. 1994 land use map.

The second phase of the study has the aim to create a digital terrain model (DTM) to calculate the orography of the study area. The hydrological model application requires a grid model (with 1x1 km cells) containing the average elevation of each cell. The DTM was obtained by the procedure described below (Fig. 4). It was, first, created the vector digital model (TIN – Triangular Irregular Network) from the contour lines of the vector GIS database “CT10” of Lombardy Region (equidistance = 10 m). From this was then obtained a model in GRID format with cells of 1 ha (100x100 m). These cells have been reclassified on a base of 25 m elevation interval (from 280 but 1200 m above sea level). The GRID was later converted to ESRI shapefile, with a field containing the reclassified elevation. A vector grid of 1x1 km cells was then created and an overlay mapping of this with the 1 ha cells shapefile was done. The new database obtained allowed to calculate, for each of the 1km^2 cells, the "average elevation" (Ej) from the values of the 1 ha reclassified cells.

The final phase provides for the creation of a unique database containing all the information. To this end, an overlay mapping between the 1x1 km vector grid and 1954 land use first and 1994 land use after were performed. This operation allowed to calculate, for each cell, the "urbanized land", "woodland” and “vegetated land” areas for the 1954 and 1994. From the information thus obtained the final calculation for each cell of the values of CN for 1954 and 1994 was carried out. The CN (Curve Number) is a parameter that influences the empirical relationship proposed by the U.S. Soil Conservation Service (SCS) for the calculation of the potential infiltration. The CN has a principal variability linked to the main geological characteristics and land use destinations, and a secondary variability related to the soil moisture conditions before the meteoric events.

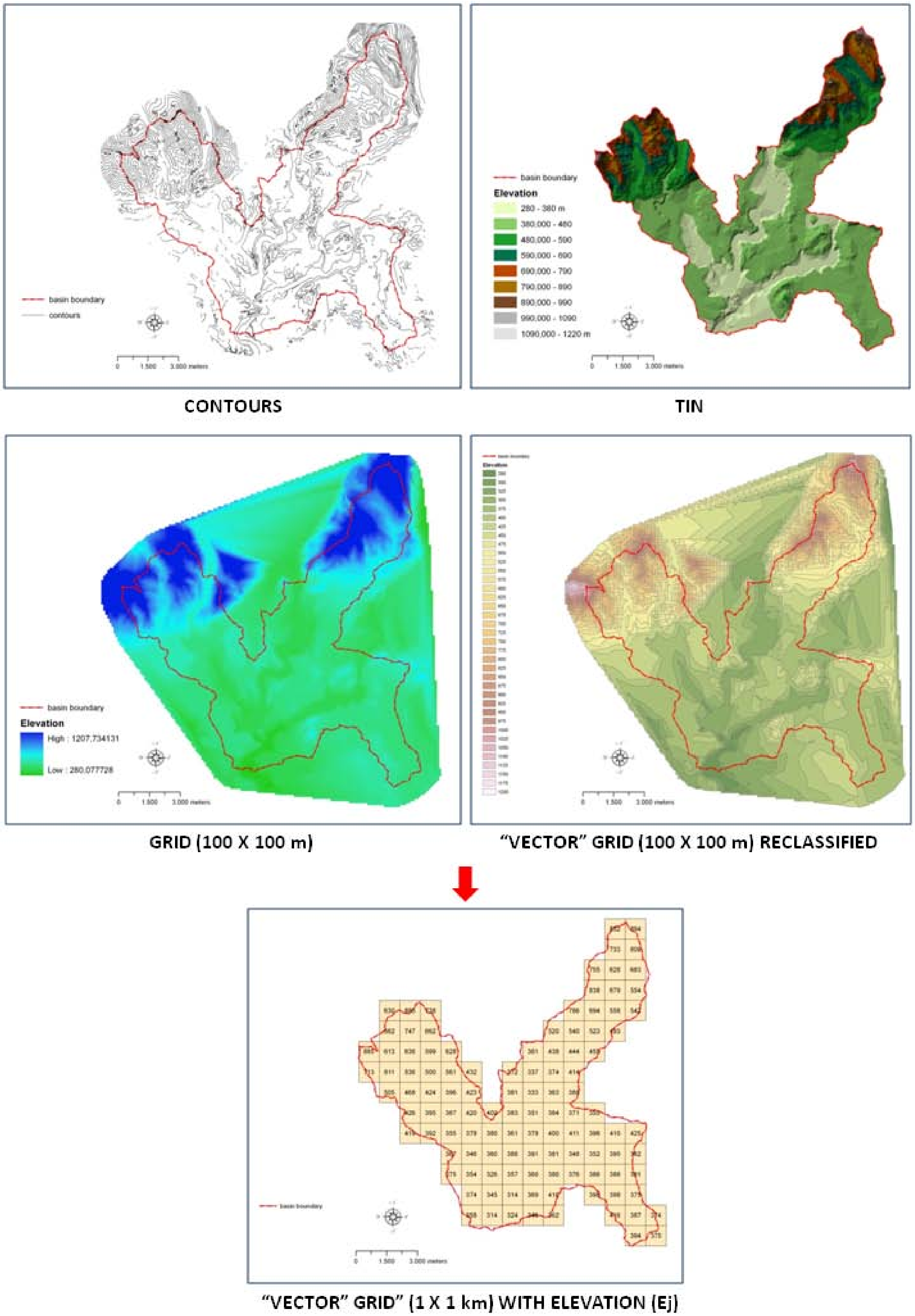

Figure 4. Grid elaboration procedure.

The SCS provides the CN values depending on the soil type in average humidity conditions, from a large number of experimental data, obtained in very different situations. Regarding the application to the Olona basin study area, the CN values were attributed as follows: “urbanized land” class, CN = 95; “woodland” class, CN = 45; “vegetated land” class, CN = 65. The choice of these values was made considering land use and geo-pedological characteristics. For each cell and for both years (1954 and 1994) the CN value has been calculated, through a “weighted average” among the different uses in the cell. The final result is the subdivision of the study in 112 1x1 km cells, for each of which the following parameters were established:

- Average elevation,
- Woodland in 1954 (in hectares),
- Vegetated land in 1954 (in hectares),
- Urbanized land in 1954 (in hectares),
- Woodland in 1994 (in hectares),
- Vegetated land in 1994 (in hectares),
- Urbanized land in 1994 (in hectares),
- Curve Number (CN) in 1954,
- Curve Number (CN) in 1994.

The distribution of flow direction and velocity over the catchment is used to define the channel network. Any cell that is not crossed by the stream network is assumed to be controlled by overland flow and its average excess rainfall is the input of the nearest down slope cell, until it is reached a cell crossed by the stream network. Then the runoff of the upslope cells travels in the stream bed and reaches the watershed closure section after a channel flow travel time $t_{channel}$. To calculate $t_{channel}$ it is required an average flow velocity computed using the Manning and the continuity equations applied to the channel:

$$t_{channel} = \frac{L n_1^{3/5}}{S_C^{0.3} \left(q / B \right)^{2/5}} \tag{1}$$

where L is the channel length, n_1 is the channel Manning roughness coefficient, q is the total upslope cells runoff, B is the channel width and S_C is the average channel slope along the L. In the hypothesis of a rainfall of uniform intensity, uniformly distributed over the watershed and of duration longer than the watershed concentration time, the time area diagram is a number of sub areas separated by isochrones, i.e. isolines of equal travel time to the outlet. The model calculates the flow pick in the outlet section Q_{max} (m^3/s) as the sum of the flow contribute q_i of all cells crossed by the stream network (the i index is referred to these N cells). The q_i discharges are calculated at the watershed concentration time t_c, i.e. the maximum value of $t_{channel}$, $t_c = max\ (t_{channel})_i$ with $i = 1,\ldots, N$.

$$Q_{\max} = \sum_{1}^{N} q_i (t_c) \tag{2}$$

The surplus water quantity $q_i \Delta t = V_{out}$ of the cell with surface A, crossed by the stream network is the sum of the output of the up flow boundary cells, not crossed by the stream, $V_{in} = q_{in} \Delta t$, of the precipitation volume PA, of the evaporation volume loss EA, of the infiltration volume loss IA and of the storage volume change SA, all in the time step Δt:

$$q_i \Delta t = PA - IA - EA - SA + q_{in} \Delta t \tag{2}$$

To calculate the three terms on the right $(P\text{-}I\text{-}S)A$ it is used a method similar to the Soil Conservation Service method. It is defined the water depth storage S in the time step Δt with the CN parameter as:

$$S = 25400 / \mathrm{CN} - 254 \text{ (mm)}. \tag{3}$$

About the initial abstraction parameter $I_a = \lambda S$ (mm), with $\lambda = 0.2$ in standard condition, but λ tend to 0 during a very strong rainfall; in this method, rainfall lasts more than the concentration time t_c, thus it is taken $\lambda = 0$. The direct cell runoff R_d is then calculated with the relation:

$$R_d = \frac{(P - I_a)^2}{P - I_a - S} = \frac{P^2}{P - S} \text{ (mm)} \tag{4}$$

where P is the total precipitation in the time step Δt. Using R_d and taking into account that evaporation is negligible during strong rainfall, the i cell contribution to the watershed runoff at time t_c on the hypothesis of a high intensity of long duration uniformly distributed rainfall, which last after t_c a time Δt=1 hour, is:

$$q_i = \frac{R_d}{3.6} + q_{in} \text{ (m}^3\text{/s)} \tag{5}$$

where the cell surface measures 1 km^2 and q_{in} is obtained as the sum of the direct runoffs coming from the nearest external cells, not crossed by the stream:

$$q_{in} = (\sum_j \frac{R_{d_j}}{3.6}). \tag{6}$$

With this method it is possible to give a value to the basin runoff for different rainfall in a changing scenario, using a single parameter CN to define the land use change during high intensity events. To calculate a range of values for precipitation P in the upper Olona watershed, we use rainfall data series of three meteorological stations near and inside the watershed: Varese, Ponte Tresa and Venegono Inferiore. Each of these stations has a working period which lasts many years, covering the period of great land use changing, and the local values are extended to the watershed using the Thiessen polygon method. The rainfall data are computed using a depth duration frequency curve calculated for two fixed return periods T=5 and T=100. Giving a year series of extreme rainfall data the depth duration frequency curve parameters c and n are calculated in each station with a regression process by the statistical rainfall values obtained with a Gumbel distribution (preferred to TCEV after Maione 2008) for the two return periods chosen:

$$h = c_T t^{n_T} \tag{7}$$

Rainfall values h are then computed in each Thiessen polygon using for t the concentration time t_c, but t_c from Eq. 1 is a function of q and so it must be calculated with an iterative process for the two frequency conditions chosen. To start the iterative process it is used for t the watershed concentration time t_c calculated with the Kirpich formula, using the main channel length from divide to outlet l= 23700 m and the average channel slope S =0.026 (the Kirpich concentration time t_c is 3.1 hours). The concentration time t_c of the two scenarios chosen is then calculated with the model application iteratively. The process stops when the results match the experimental data available.

The Olona yearly maxima watershed discharges at Ponte Gurone have been monitored in the period 1939 – 1984 with only one missing year 1943 (Fig. 5). The polynomial regression line of the measured discharges biases to rise. This data set shows an evident trend change after 1965. In this work the data of the two periods 1939 – 1965 and 1966 – 1984 have been statistically analyzed independently. The discharges with a return period of 5 years and of 100 years have been calculated for the two data sets. The first period is referred to the 1954 scenario and the second to the 1994 scenario. These values are then used to calibrate the model parameters.

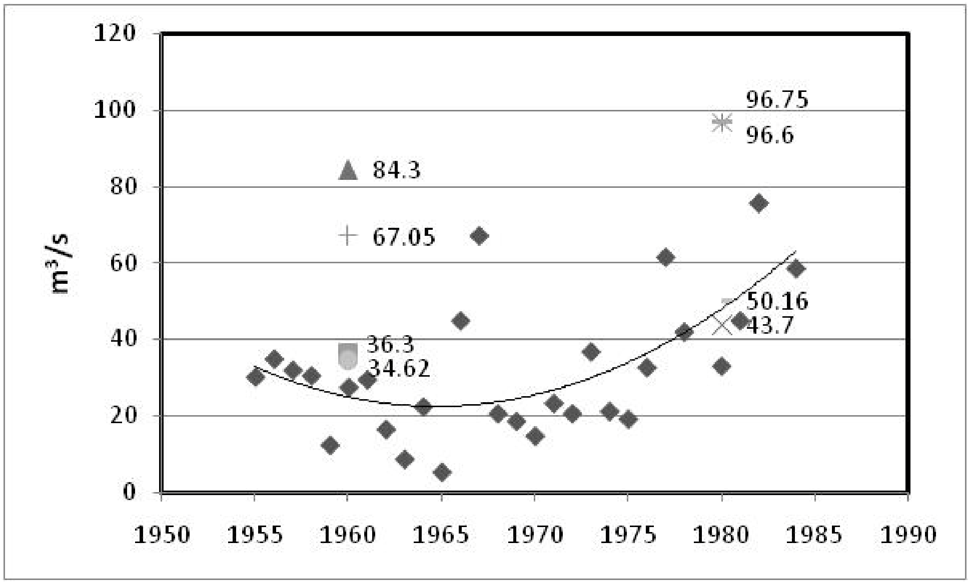

Figure 5. Yearly maximum measured discharges at Ponte Gurone (m^3/s); Q_5 and Q_{100}, Q_{5mod} and Q_{100mod} in the two periods with different scenarios.

RESULTS AND CONCLUSIONS 2 The model calculates the direct runoff in each cell, using a similar SCS-CN method. This is obviously a rough model, but after calibration it could be satisfactory to compare the watershed runoff in the two chosen scenarios. Knowing the cell slope direction the model evaluates the inflow and the outflow of the nearest cells and, if the cell is crossed by a channel stream, the total cell discharge contribution in the watershed outlet section. In the hypothesis of a uniform rainfall which lasts more than the concentration time, the total outlet flow is the cells output flow sum. This model, defined as the cell CN parameter, features only two other parameters: the λ coefficient to calculate the initial abstraction I_a and the total travel time for the more distant cell to the outlet, i.e. the concentration time t_c. The frequency annual maxima discharges obtained from the two real measured sets of the watershed outflows are for the first period (1939 – 1965) Q_5=34.62 and Q_{100}=67.05 (m^3/s) and for the second period (1966 – 1984) Q_5=50.16 and Q_{100}=96.75 (m^3/s). Using depth duration frequency curves calculated for T=5 and T=100 in the three previous stations to compute the project precipitations P_5 and P_{100}, the model results fit annual maxima discharges Q_5 and Q_{100} with λ=0 and t_c =3.4 hours (not far from Kirpich concentration time). The values for the first period are Q_{5mod}=36.3 and Q_{100mod}=84.3 (m^3/s) and for the second period Q_{5mod}=43.7 and Q_{100mod}=96.6 (m^3/s) (see Fig. 5).

Urban expansion has increased waterproof surfaces within the basin, causing less infiltration and a quicker runoff with higher outflow peaks. In this small basin, urban development has increased the outflow peaks by 45% due to a doubling of the urban surface from 9% to18%. Land use is, then, strictly correlated to the catchment hydrology. The land use planning policy must recognize the importance of the soil physical process knowledge and must calculate in the project economy the cost of the works necessary to reduce the effects of urban extension and of land use change. It could be of interest to link the land use planning policies with a local knowledge in the environmental evaluation of the hydrological processes.

REFERENCES

Bloschl, G., Ardoin-Bardin, S., Bonell, M., Dorninger, M., Goodrich, D., Gutknecht, D., Matamoros, D., Merz, B., Shand, P., Szolgay, J., 2007. At what scales do climate variability and land cover change impact on flooding and low flows? Hydrological Processes 21: 1241-1247.

Bronstert, A., Neidhofer, F. and Burger, G., 2002. Effects of climate and land use change on storm runoff generation: present knowledge and modeling capabilities. Hydrological Processes 16: 509-529.

Choi, JY., Engel, BA., Muthukrishanan, S., Harbor, J., 2003. GIS Based Long Term Hydrologic Impact Evaluation for Watershed Urbanization. Journal of the American Water Resources Association 39(3): 623-635.

Croke, B FW., Merritt, WS., Jakeman, AJ., 2004. A dynamic model for predicting hydrologic response to land cover changes in gauged and ungauged catchments. Journal of Hydrology 291 (1/2): 115-131.

Engel BA., Choi, JY., Harbor, J., Pandey, S., 2003. Web-based DSS for hydrologic impact evaluation of small watershed land use changes. Computers and Electronics in Agriculture 39: 241-249.

Hollis, GE., 1975. The effects of urbanization on floods of different recurrence interval. Water . Forest Science 21: 141-148.

Liu, YB., Gebremeskel, S., De Smedt, F., Hoffmann, L., Pfister, L., 2006. Predicting storm runoff from different land-use classes using a geographical information system-based distributed model. Hydrological Processes 20: 533-548.

Matheussen, B,. Kirschbaum, RL., Goodman, IA., O'Donnell, GM., Lettenmaier, DP, 2000. Effects of land cover change on streamflow in the interior Columbia River Basin (USA and Canada). Hydrological Processes 14 (5): 867-885

Mishra, SK., Jain, MK., Bhunya, PK., Singh, VP., 2005. Field applicability of the SCS-CN-based Mishra-Singh general model and its variants. Water Resources Management 19: 37-62.

Niehoff, D., Fritsch, U., Bronstert, A., 2002. Land-use impacts on storm-runoff generation: scenarios of land-use change and simulation of hydrological response in a meso-scale catchment in SW-Germany. Journal of Hydrology 267 (1-2): 80-93.

Patil, JP., Sarangi, A., Singh, OP., Singh, AK., Ahmad, T., 2008. Development of a GIS Interface for Estimation of Runoff from Watersheds. Water Resources Management 22: 1221-1239.

Pauleit, S., Ennos, R., Golding, Y., 2004. Modeling the environmental impacts of urban land use and land cover change-a study in Merseyside, UK. Landscape and Urban Planning 71: 295-310.

Pielke, RA., 2005. Land use and climate change. Atmospheric Science Volume 310: 1625-1626.

Samaniego, L., Bardossy, A., 2005. Robust parametric models of runoff characteristics at the mesoscale. Journal of Hydrology 303 (1/4):136-151.

Storck, P, Bowling, L, Wetherbee, P, Lettenmaier, D, 1998. Application of a GIS-based distributed hydrology model for prediction of forest harvest effects on peak stream flow in the Pacific Northwest. Hydrological Processes 12: 889-904.

VanShaar, JR., Haddeland, I., Lettenmaier, DP., 2002. Effects of land-cover changes on the hydrological response of interior Columbia River basin forested catchments. Hydrological Processes 16 (13): 2499-2520.